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13. ABSTRACT *(Maximum 200 words)*

This report presents a summary of research results obtained during the course of this grant in the area of distributed signal detectionand decision fusion. Specifically, distributed detection and estimation with fuzzy information, intelligent CFAR detection, computational algorithms for system design and BDT based signal classification were considered. A brief discussion of these results is provided here. For more details, the reader is referred to the list of published papers.

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FINAL REPORT

DISTRIBUTED DETECTION THEORY AND DATA FUSION

Grant No. F49620-96-1-0185

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1. Introduction

A team of sensors or processors operating on a probabilistic information system in order to reach a global objective is often encountered in practice. The sensors, often geographically separated, observe the common phenomenon of interest. The sensors are linked to a global processor, or data fusion center by means of communication channels. In a conventional centralized processing system, the sensors transmit their observations without any processing done locally, and the global processor incorporates them in an optimal fashion and reaches the global objective. However, in many practical situations the channels linking the local sensors to the data fusion center have finite channel capacities. Transmission of the local sensor observations 'as is' to the fusion center over such rate-constrained channels requires a longer data transmission period which conflicts with the need for reaching the global objective in a shorter time. Also, in some cases it is desired to reduce communication as much as possible to avoid being detected.

In decentralized systems, the local sensors process their own data and a compressed version of the data is conveyed to the global processor. The global processor combines all the compressed information from the local sensors. Decentralized systems display higher survivability, and reliability in situations where one or more sensors fail, by limiting the possibility of corrupt data from faulty sensors dominating the global result. Also, partial data processing at the local sensors eases the computational burden of the global processor. Thus, the decentralized system possesses many desirable features from a practical standpoint, which justifies the information loss incurred due to data transmission at a reduced rate.

During this research period, we focussed on the problems of signal detection both in centralized and decentralized frameworks. A number of results were obtained on different aspects of these problems. A summary of these accomplishments is provided in Section II. Research carried out under this grant is being used by a number of industrial and government organizations. Section III contains an example of technology transition. A list of publications supported by this grant is provided in Section IV.

2. Summary of Accomplishments

Distributed Detection with Fuzzy Data

In many practical situations involving distributed detection, the mathematical model used to represent the physical phenomenon encountered by the decentralized detection or estimation system is not completely defined, i.e., one or several of the parameters of the mathematical model may be unknown or partially known. In addition, there may be measurement inaccuracies attached to the sensors. However, most of the work on decentralized detection systems has been conducted on the assumptions that the mathematical models are completely known and that exact measurements are available. The use of fuzzy sets in representing uncertainty in signal detection problems has been shown to complement the conventional approaches using probabilistic modeling. This formulation has been considered in the context of decentralized detection and estimation systems in this research period.

We concentrated on two distinct approaches that use fuzzy sets in modeling uncertainty. In one approach, the sample information available from the physical phenomenon of interest is

assumed to be vague. The vagueness of the data is represented by means of 'fuzzy events' defined over the real line. In the second approach, one or more parameters in the mathematical model describing the physical phenomenon are assumed to be unknown. A fuzzy set representation is employed in modeling the unknown parameters. We introduce a decentralized signal detection system where the uncertainties regarding the physical phenomenon of interest are modeled by means of fuzzy sets. Bayesian approach is used in system design. We also analyzed the issue of data compression when the available information at each sensor is described by a large number of fuzzy events. Several suboptimal schemes for fuzzy information compression were also presented. Nonparametric detection schemes, for a multi-sensor system using fuzzy information, were discussed and the effect of fuzziness on system performance was illustrated. The issue of parameter estimation in multi-sensor systems with fuzzy information was also addressed.

We also derived a multi-sensor decision fusion scheme where the local sensor decision probabilities are modeled as fuzzy events. We designed the fusion rule for the set of local decisions with fuzzily modeled decision probabilities. The Bayesian decision criterion is modified in order to accommodate the fuzzy parameters present in the probabilistic model. A fuzzy modeling approach to the detection of a weak signal in additive noise is also presented. The decision rule resulting from Bayes criterion was shown to be a constant false alarm rate detector.

Intelligent CFAR Processing Based on Data Variability

The CFAR problem involves performing target detection by comparing radar returns to an adaptive threshold such that a constant false alarm rate is maintained. To accomplish this goal, a

CFAR processor dynamically determines a detection threshold by estimating the local background noise/clutter power and multiplying this estimate by a scaling constant based on the desired Pfa. In this manner, CFAR performance is maintained in an environment of unknown and time-varying noise power. An intelligent CFAR processor to perform adaptive threshold target detection was designed and analyzed. It employs a composite approach based on the well-known CA-CFAR, SO-CFAR, and GO-CFAR processors. Data in the reference window is used to compute a second-order statistic called the variability index (VI) and the ratio of the means of the leading and lagging windows. Based on these statistics, the VI-CFAR dynamically tailors the background estimation algorithm. The VI-CFAR processor provides low loss constant false alarm rate performance in a homogeneous environment and also performs robustly in non-homogeneous environments including multiple targets and extended clutter edges. Due to its simplicity of implementation, it can easily be used with existing CFAR processors.

Data Transmission in Multiterminal Systems

Efficient information transmission between peripheral terminals and the central processing unit is vital in distributed detection systems. In general low transmission rates are sought after because of the limited a capacity of communication links and of the reliability and survivability reasons. This kind of a problem can be formulated as a multiterminal source coding problem. Efficient use of the correlation between the terminals is the key in achieving low transmission rates. We introduce two new concepts that characterize the correlation between two terminals. Our basic idea is to establish a link between the two terminals to resolve the

conditional entropy. Given such a link, the two terminals are statistically identical, i.e. observation of one terminal is completely determined by the observation of the other terminal. Using these concepts, we have studied a two terminal parallel system in which the terminals observe correlated symbol streams. Each stream is made up of uniformly distributed i.i.d. M-ary symbols. The correlation between the two terminals is modeled as a M-ary symmetric channel. The goal is to establish a link at the central processor using minimum transmission rate at each terminal. We have shown that the minimum transmission rate at a terminal is equal to the conditional entropy of the observation of this terminal given the observation of the other terminal. Based on the information received from the terminals, the central processor can view the two terminals as statistically identical.

A Practical Solution to the Multiple Hypothesis Testing Problems

Multiple hypothesis testing problems have been widely studied. The most important result on this kind of problems is perhaps that an optimal solution is a Bayesian procedure. In many such problems, it is assumed that the prior probabilities are known, then the goal is to minimize the average cost of the test. However, when the prior probabilities are not known, the problems become much more difficult. One approach is to formulate a minimax problem. Unfortunately, many problems can not be formulated as minimax problems. An even bigger obstacle is that even after the goal is appropriately formed, the prior probabilities of the solution are still much difficult to compute. Analytical results on the prior probabilities are obtained only when the probability distribution function of the observation belongs to some specific families.

To obtain a practical solution to the multiple hypotheses testing problem, we take the following steps. First, we assume the goal can be expressed as a set of constraints on conditional cost for each hypothesis, i.e. for any given test, we will be able to tell when the resulting conditional costs are satisfactory. Thus we eliminate the need for knowledge regarding prior probabilities and generalize the goal beyond minimax criterion. Next we break the problem into two parts, searching for the prior probabilities and evaluation of conditional costs given prior probabilities. We assume the latter can be readily carried out by a known process. This is a fair assumption since in most situations we will be able to obtain the performance of the test. Now we focus on the search for the prior probabilities. Our basic idea is to the successively modify the prior probabilities until the resulting conditional costs meet all the constraints. This is carried out by an algorithm that makes use of certain geometric properties of the conditional costs. In particular, we have studied the problem in which many hypotheses are tested against a single hypothesis. An example of such a problem is signal detection under a class of noise types. In this problem, each false probability rate is constrained, then the detection probability is maximized. This is essentially a generalized Neyman-Pearson problem. We are currently applying our algorithm to more general formulations.

Multistage Detection in a Distributed Environment

One stage distributed M-ary decision fusion problems have been shown to be very difficult. To ease this difficulty, we break it into a sequence of binary problems. This can be done by a hierarchical partition of the signal space. Such a partition can be represented by a binary

decision tree (BDT). To efficiently navigate this tree, we allow the fusion center to choose the path for the sensors. We have devised two methods for constructing a BDT. These methods are based on a class of information distance measures between the signals. Given a BDT, we have obtained the structure of the optimal decision rules. These rules are similar to the Bayesian procedures except that the prior probabilities are replaced by constant weights that could be negative. We have applied our result in a parallel system consisting of a fusion center and three identical sensors. The system is used to detect eight equally likely signals. These signals are evenly spaced on the real line. The sensor observations are subject to independent Gaussian noise. Our numerical result shows that properly constructed BDTs significantly outperform the one-stage M-ary decision fusion scheme.

3. Technology Transition

The distributed detection methodology developed under this grant has been considered for adoption by a number of industrial and government organizations. As an example, Pacific Sierra Research is currently investigating its use for IMINT Change detection fusion for the Dynamic Data Base program of DARPA. A number of imaging sensors are used to generate change reports (two methods of change detection using SAR, and a change detection using EO). The system exhibits a large number of false alarms. A decision fusion approach is being considered to control false alarms. Best local thresholds and fusion rules are determined to optimize the overall system performance. Under the same DARPA program, ERIM is considering the distributed sequential detection methodology for classification purposes.

4. List of Publications

Book:

1. P.K. Varshney, *Distributed Detection and Data Fusion*, Springer-Verlag, 1997.

Journal Papers:

1. S. ALHAKEEM and P.K. VARSHNEY, "Decentralized Bayesian Detection with Feedback." *IEEE Trans. on Systems, Man and Cybernetics*, Vol. 26, pp. 503-513, July 1996.

2. P.K. Varshney, "Scanning the Issue," Guest Editorial in the *Proceedings of IEEE*, Vol. 85, pp. 3-5, January 1997.

3. R. Viswanathan and P.K. Varshney, "Distributed Detection with Multiple Sensors: Part I - Fundamentals," Invited Paper in the *Proceedings of the IEEE*, Vol. 85, pp. 54-63, January 1997

4. V.N.S. Samarasooriya and P.K. Varshney, "Decentralized Signal Detection with Fuzzy Information," *Optical Engineering*, Vol. 36, pp. 658-668, March 1997.

5. T. Tsao, P.K. Varshney, D. Weiner, H. Schwarzlander, M. Slamani, and S. Borek, "Ambiguity Function for a Bistatic Radar," *IEEE Trans. on Aerospace and Elect. Syst.*, Vol. 33, pp. 1041-1051, July 1997.

6. C.T. Yu and P.K. Varshney, "Sampling Design for Gaussian Detection Problems," *IEEE Trans. on Signal Processing*, Vol. 45, pp. 2328-2337, Sept. 1997.

7. P.K. Varshney, "Multisensor Data Fusion," *Electronics and Communications Engineering Journal*, Vol. 9, pp. 245-253, Dec. 1997.

8. C.T. Yu and P.K. Varshney, "Paradigm for Distributed Detection Under Communication Constraints," *Optical Engineering*, Vol. 37, pp. 417-426, February, 1998.

9. C.T. Yu and P.K. Varshney, "Bit Allocation for Discrete Signal Detection," *IEEE Trans. on Communication*, Vol. 46, pp. 173-175, February, 1998.

10. C.H. Gowda, M.K. Uner, P.K. Varshney and R. Viswanathan, "Distributed CFAR Target Detection," *Journal of the Franklin Institute*, Vol. 336, pp. 257-267, March 1999.

11. F. Gini, F. Lombardini, and P. K. Varshney, "On Distributed Signal Detection with Multiple Local Free Parameters", *IEEE Trans. on AES*, Vol. 35, pp. 1457-1466, Oct. 1999.

12. V. N. S. Samarasooriya and P. K. Varshney, "A Fuzzy Modeling Approach to Decision Fusion Under Uncertainty", Accepted to appear in *Fuzzy Sets and Systems*.

Conference Papers:

1. V.N.S. Samarasooriya and P.K. Varshney, "Signal Detection in Multiple Sensor Systems with Fuzzy Information," Proc. Of the 1996 Conference on Information Sciences and Systems, Princeton, N.J., March 1996.

2. C.H. Gowda, R. Viswanathan, M.K. Uner and P.K. Varshney, "Distributed CFAR Target Detection," Proc. Of the Workshop on Foundations of Information/Decision Fusion, Washington, D.C., Aug. 1996.

3. V.N.S. Samarasooriya and P.K. Varshney, "A Fuzzy Modeling Approach to Decision Fusion Under Uncertainty," Proc. Of the 1996 IEEE/SICE/RSJ Int. Conf. On Multisensor Fusion and Integration for Intelligent Systems, Washington, D.C., Dec. 1996.

4. C.T. Yu and P.K. Varshney, "Decision Fusion Using Channels with Communication Constraints," Proc. Of SPIE Conf. On Sensor Fusion: Architectures, Algorithms and Applications, Orlando, FL, April, 1997.

5. M. Smith and P.K. Varshney, "VI-CFAR: A Novel CFAR Algorithm Based on Data Variability," Proc. of the 1997 IEEE National Radar Conference, Syracuse, NY, May 1997.

6. V.N.S. Samarasooriya and P.K. Varshney, "Decentralized Parameter Estimation with Fuzzy Information," Proc. Of the 1997 Annual Meeting of the North American Fuzzy Info. Proc. Society, Syracuse, NY, September, 1997.

7. F. Gini, F. Lombardini, P.K. Varshney and L. Verrazzani, "Distributed Detection with Multiple Local Free Parameters," Proc. Of the 1998 Conf. On Info. Sciences and Systems, Princeton, N.J., March, 1998.

8. Q. Zhang and P. K. Varshney, "A Generalization of Korner-Marton Result on Multiterminal Source Coding", Proc. of the IEEE Int. Symp. on Information Theory, Boston, August 1998.

9. P. K. Varshney, "On Distributed Detection and Data Fusion", Proc. of EuroFusion'98, Malvern, U.K., Oct. 1998.

10. T. Kasetkasem and P. K. Varshney, “Soft Handoff Strategies in Distributed Sensor Systems”, Proc. of the Asilomar Conf. on Circuits, Systems and Computers, Monterey, Nov. 1998.

11. Q. Zhang, P. K. Varshney and Y. Zhu, “On the Design of Extended Neyman-Pearson Hypothesis Tests”, Proc. SPIE’99, Orlando, March 99.

12. Q. Zhang and P. K. Varshney, “Towards the Fusion of Distributed Binary Decision tree Classifiers”, Proc. Fusion ’99, Sunnyvale, CA, July 1999.

Dissertations and Theses:

1. T. Kasetkasem, “On Communication Structure Planning for Multisensor Detection Systems,” M.S. Thesis, May 1999.

2. V. Samarasooriya, "Decentralized Detection and Estimation with Fuzzy and Asynchronous Observations," Ph.D. Dissertation , December 1996.

3. M. Smith, "Application of the VI Statistic to Radar CFAR Processing," Ph.D. Dissertation, June 1997.